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Operability of Integrated Gasification Combined Cycle power plant with SEWGS technology for pre-combustion CO_2 capture

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Abstract

This paper investigates the performance of an integrated gasification combined cycle (IGCC) power plant incorporating a sorption enhanced water gas shift (SEWGS) process for pre-combustion CO_2 capture at part-load conditions. The multi-train SEWGS process operates on a cyclic manner based on a pressure swing adsorption (PSA) process and reaches a cyclic steady state. Each train consists of eight SEWGS vessels. A H_2-rich stream which is produced at high temperature and pressure is sent to a gas turbine (GT) as an almost carbon-free fuel for power generation. A CO_2-rich stream, the secondary product of the SEWGS process, is released from the solid adsorbent at low pressure. Dynamic mathematical modeling of the SEWGS system developed previously is used to simulate the performance of the SEWGS system at different part-loads. A control strategy including a buffer tank and a closed-loop proportional integral (PI) controller is designed to provide the required amount of the fuel to the GT at full-load and part-load modes of operation. The control system performance is very important to provide a fuel from the SEWGS system that fulfils the requirement of the GT with respect to fuel pressure and heating value variations. Simulation results show when the GT load is changed, the control system functions properly and provides the corresponding GT fuel flow after a new steady-state condition is reached. The H_2-rich stream flow rate fluctuation, associated with the cyclic operation of the SEWGS process, is reduced from ~±14% to ~±1% under the effect of the designed PI controller. On the other hand, when a load change is given to the GT, operation of the entire IGCC plant is dictated by the rate of change of the SEWGS system. The load gradient of the SEWGS process achieved from the part-load simulations is ~2% load/min. The SEWGS system is not able to respond to load changes as rapid as the GT. This will reduce the operation flexibility of the entire IGCC Plant. However, the addition of the intermediate buffer tank improves the operation flexibility of the GT as long as the pressure variation in the tank falls within the acceptable range.

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Nomenclature

Abbreviations	
ASU	Air separation unit
CSS	Cyclic steady state
GT	Gas turbine
HP	High pressure
HTC	Hydrotalcite
HTS	High temperature shift
IGCC	Integrated gasification combined cycle
LP	Low pressure
LTS	Low temperature shift
NGCC	Natural gas combined cycle
PI	Proportional integral
PSA	Pressure swing adsorption
SEWGS	Sorption enhanced water gas shift
SP	Set-point
ST	Steam turbine
Symbols	
$\dot{m}_{fuel.measured}$	Measured fuel mass flow rate (kg/s)
$\dot{m}_{fuel.setpoint}$	Fuel mass flow rate set-point value (kg/s)
error	Difference between the measured fuel mass flow rate and its set-point value (kg/s)
K_c	Anti-windup coefficient (-)
K_i	Integral coefficient (-)
K_p	Proportional coefficient (-)
$U_{controller}$	Classical PI controller output (kg/s)
U_i	The integral term (kg/s)
U_p	The proportional term (kg/s)
Xvalve_act	Control valve actuator opening (-)

1. Introduction

Integrated gasification combined cycle (IGCC) is a power production technology in which a solid feedstock such as coal is gasified and converted to syngas. Syngas is basically a mixture of carbon monoxide and H_2 along with some minor components (e.g. carbon dioxide, water vapor, hydrogen sulphide, ammonia, etc.). The syngas is then converted to electricity in a combined cycle power block which consists of a gas turbine (GT), steam turbine (ST) and heat recovery steam generator (HRSG).

IGCC plants can take the advantage of the high pressure of the syngas stream for utilizing a CO_2 capture process to remove the CO_2 from the syngas before combustion in the GT. Physical absorption-based processes by using physical solvents, such as Selexol or Rectisol is the most developed and mature pre-combustion CO_2 capture option. These solvent-based absorption processes operate at a fairly low temperature. Thus, the gas stream entering the absorber must be significantly cooled down. This results in either loss of high amount of the available energy or high capital costs for heat recuperation [1]. It is therefore worth to investigate alternative CO_2 capture processes for IGCC applications with lower energy penalties than the low-temperature capture processes. Recently, solid adsorption-based processes, as an alternative to physical absorption-based processes have attracted growing attentions [2-6]. A novel pre-combustion CO_2 capture concept called sorption enhanced water gas shift (SEWGS) combines both the water gas shift (WGS) reaction and CO_2 capture in one single unit at elevated temperatures typically between ~350-550°C [7]. The CO_2 adsorption on a solid material shifts the equilibrium of the WGS reaction towards higher conversions of the CO into the CO_2. In contrast, conventional pre-combustion CO_2 capture technologies typically consist of two stages of high temperature shift (HTS) and low temperature shift (LTS) reactors followed by a CO_2 capture unit. The CO_2 capture processes are typically based on physical absorption at low temperature, i.e. a Selexol-based process. Also there are intermediate cooling and reheating stages in such methods to prepare the fuel as per GT requirement [8, 9]. The SEWGS technology has the potential to lower the efficiency penalty of power plants with CCS technologies by combining the WGS reaction and CO_2 capture steps, as well as eliminating the need for cooling and reheating of syngas streams, as is done in conventional processes. Inherently, it is a dynamic process, which operates based on a pressure swing adsorption (PSA) process and undergoes a cyclic operation. The process reaches a cyclic steady state (CSS) after a number of cycles. Then almost an identical pattern of variations in product gas thermodynamic properties is observed repeatedly in each cycle [10, 11]. A H_2-rich stream at high pressure and a CO_2-rich stream at low pressure are produced. To achieve a continuous production of the H_2-rich and CO_2-rich products out of the batch SEWGS single reactor process, it is common to utilize a multiple reactor system for the PSA-based SEWGS process.

Lately, the technology has been attracted a growing interest for pre-combustion CO_2 capture application in power plants. However, it is still far from being considered as a well-developed and mature technology and further investigation and research works are yet to be carried out on different aspects of this technology. A research activity undertook screening studies on a number of potential CO_2 adsorbent materials to select the most suitable adsorbent. Then, a steady-state simulation of a natural gas combined cycle (NGCC) power plant integrated with the SEWGS process for pre-combustion CO_2 capture was carried out using the data achieved from the experimental work on the selected adsorbent material (K_2CO_3 promoted hydrotalcite (HTC)) [12]. Further experimental and theoretical research studies on the SEWGS process, including development of proper CO_2 adsorbent materials were carried out within the CACHET and later CAESAR projects [13, 14]. It was shown that the steam consumption and energy penalty were reduced by using the SEWGS technology for CO_2 capture compared to the conventional solvent-based pre-combustion CO_2 capture technologies [15]. A recent steady-state performance assessment of both NGCC and IGCC power plants integrated with the SEWGS process from thermodynamic and economical points of view was performed within the CAESAR project [7, 16]. The SEWGS system was a multi-train system, where each train was comprised of a number of reactors operating based on a SEWGS cycle configuration. The simulation results were indicated in terms of the efficiency and carbon capture ratio and compared with reference cases. The new K_2CO_3 promoted HTC material developed in the CAESAR project demonstrated catalytic properties and capability of H_2S and CO_2 co-adsorption. The SEWGS reactors were assumed adsorbent-filled reactors [7].

On the other hand, on a system level, there are not works investigating the performance of IGCC power plants integrated with PSA-based SEWGS process at transient and part-load conditions. Moreover, the periodic nature of the SEWGS process, in contrast with many typical processes which reach steady state, needs to be factored in when the process is integrated into an IGCC plant for pre-combustion CO_2 capture.

This work is therefore concerned with further control of the SEWGS process to fulfil the requirements of the GT with respect to fuel pressure and heating value. A dynamic detailed mathematical model of a multi-train SEWGS process which was previously developed is used in this work for simulation of the SEWGS process at different part-loads [17, 18]. A control strategy is designed to control the H_2-rich stream coming from the SEWGS system before it is sent to the GT. The dynamics of the SEWGS is revealed. This facilitates to understand whether the SEWGS process can follow the GT load changes. Also the impact of the SEWGS process on the operation flexibility of the IGCC plant is discussed.

2. IGCC integrated with the SEWGS process

A schematic diagram of an IGCC integrated with the SEWGS process for pre-combustion CO_2 capture is shown in Fig. 1. The IGCC power plant reference model from the European Benchmarking Task Force (EBTF) with two conventional HTS and LTS reactors followed by a solvent-based pre-combustion CO_2 capture unit is used [19]. However, in the present work the conventional HTS and LTS reactors as well as the CO_2 separation unit are replaced by the SEWGS vessels.

The gasification block is composed of an entrained-flow gasifer and air separation unit (ASU). Coal is partially oxidized at high temperature and pressure with oxygen (produced by the ASU) and steam to generate syngas. In the gas clean-up block, the syngas generated by the gasifier is further treated for the particulates and H_2S removal. The H_2S-rich gas is further processed in a claus plant to obtain valuable by-products. A sulphur-free syngas is then fed to the SEWGS process, so called sweet SEWGS. The detrimental effect of H_2S on the stability and long term CO_2

adsorption capacity of the K_2CO_3-promoted HTC considered in this work is the reason for choosing the sweet SEWGS process [9]. Two separate streams of the H_2-rich and CO_2-rich are produced in the SEWGS system. The H_2-rich stream enters the GT within the combined cycle block for combustion. The combined cycle block includes the GT, ST and HRSG. The high temperature of the H_2-rich stream is favoured by the GT from the efficiency point of view. The H_2-rich stream coming from the SEWGS system has almost constant temperature and pressure (~500ºC, ~27 bar), but the mass flow rate fluctuates over time (~±14%) [17].The GT requirement of having a smooth fuel heat input at any given load of operation necessitates further control of the H_2-rich stream before it is sent to the GT.

Low pressure (LP) and high pressure (HP) steam required by the SEWGS system for the rinse and purge steps are supplied from the combined cycle.

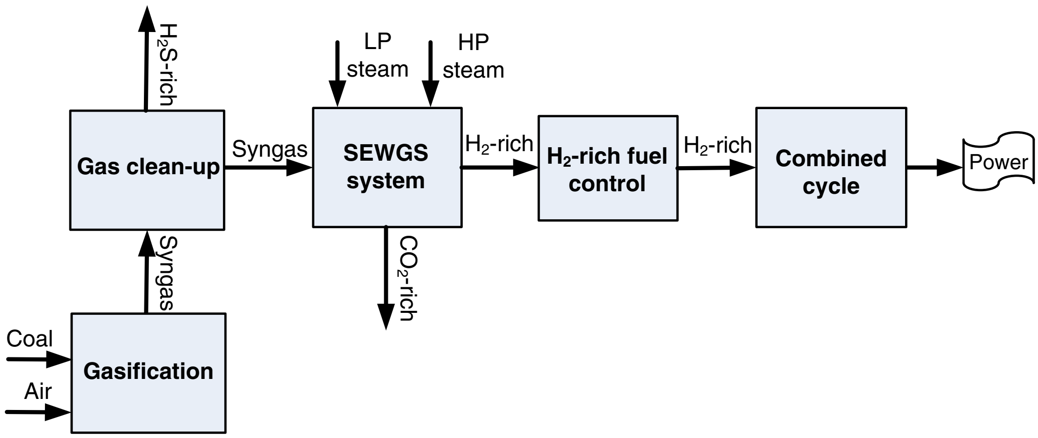

Fig. 1. A block diagram of an IGCC power plant integrated with the SEWGS process for CO_2 capture

2.1. SEWGS system layout

A top view of the SEWGS system is shown in Fig. 2. It consists of ten trains operating in parallel, where each train includes eight SEWGS vessels operating in a cyclic manner based on a PSA process. Each SEWGS reactor is packed with a mixture of the WGS catalyst and K_2CO_3 promoted HTC adsorbent and undergoes a sequence of steps according to a defined cycle configuration [17]. The SEWGS cycle configuration incorporates a sequence of steps including, feed, rinse (counter-current with HP steam), three pressure equalization (by connecting a pair of reactors), depressurization, purge (counter-current with LP steam) and repressurization (counter-current with part of the H_2-rich product gas). The H_2-rich stream is produced during the feed step where the combined WGS reaction and simultaneous CO_2 adsorption take place. The CO_2-rich stream is released during the depressurization and purge steps, through the regeneration of the solid adsorbent at atmospheric pressure. The multi-reactor system makes it possible to achieve close to continuous operation of SEWGS process, even if each reactor vessel functions as a batch process.

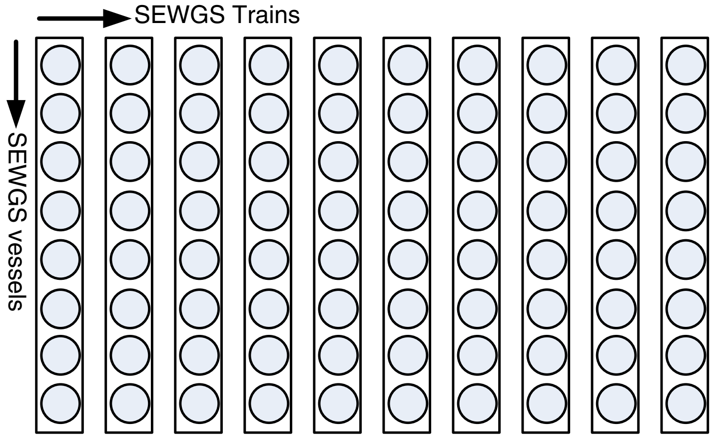

Fig. 2. The SEWGS multi-train system top view; ten trains operating in parallel, eight vessels in each train operating based on a cyclic PSA process

2.2. Fuel control strategy

The cyclic operation characteristics of the PSA-based SEWGS process leads to the production of the H_2-rich stream with repeated fluctuations over time, when the CSS is reached [17]. A closed-loop control strategy is thus designed to smooth out fluctuations in the H_2-rich stream flow rate before it is sent to the GT. As a part of the control system, a buffer tank is placed downstream of the SEWGS process to damp out a large portion of the H_2-rich fuel flow fluctuation (see Fig. 3).

A proportional integral (PI) controller which incorporates a control valve undertakes further control of the H_2-rich fuel with respect to pressure and mass flow rate. The control system is designed to control the H_2-rich fuel mass flow rate according to a set-point value. The set-point value of the fuel mass flow rate is determined based on the GT load. The objective of the control system in addition to smooth out the H_2-rich fuel flow fluctuation is also to adjust the H_2-rich fuel flow when the GT load is changed. The PI controller reduces the difference between the measured fuel mass flow rate and its set point value (error) by changing the valve actuator. Zero steady state error and fast transient response are the main characteristics of a well-functioning PI controller. A tuned anti-windup compensator is added to improve the performance of the closed loop PI controller with respect to the minimized transient response time. The structure of the PI controller including the anti-windup scheme is shown in Fig. 4. It is known that physical systems are subject to actuator saturation or limitation. This is called windup problem, where in the presence of saturation, controller behavior will be greatly deteriorated. However, the method to solve process control design problems in the case of existing input saturation in classical PI controllers is an introduced anti-windup approach [20]. In this paper, an anti-windup scheme is employed to prevent the controller's output, which is the valve actuator opening, X_{Valve_act}, from saturation and reduce the transient response time of the fuel mass flow rate under the effect of the controller.

The output of PI controller before the saturation block can be expressed by Equation (1):

$$U_{controller} = U_p(t) + U_i(t) \tag{1}$$

Where,

$$U_p(t) = K_p\, e(t) \tag{2}$$

$$U_i(t) = U_i\, e(t-1) + K_i \int U_p(t)\, dt + K_c \left[(X_{Valve\_act} - U_{controller}) \right] \tag{3}$$

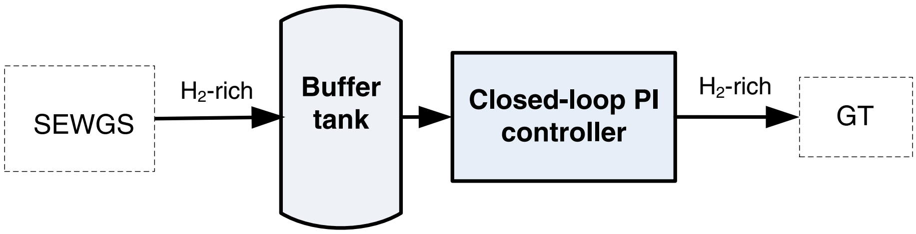

Fig. 3. H_2-rich fuel Control strategy

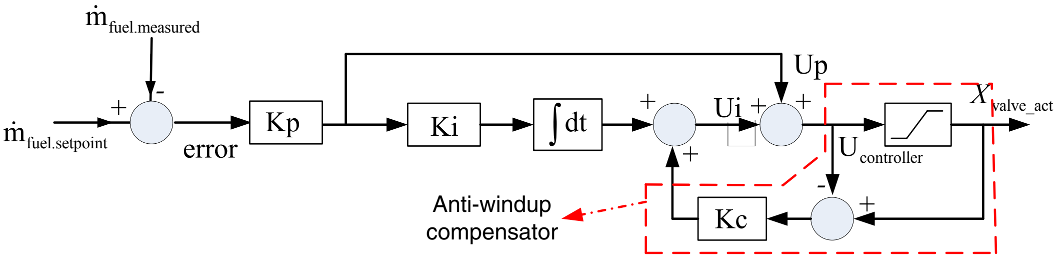

Fig. 4. The structure of PI control with anti-windup scheme

The anti-windup coefficient K_c should be in the same order as K_i (in this work: $K_i = K_c = 2.25\times10^{-4}$). The K_p is the integral coefficient ($K_p = 2.99\times10^{-3}$). The error e(t) is calculated as e(t) = error, which is the difference between the measured fuel mass flow rate at the operating point and its value corresponding to the desired mass flow rate.

3. Results and discussion

An IGCC power plant does not necessarily operate at base load. Following the variations in the electricity demand, the operation of the IGCC plant will be subject to change. In general, the operation of an IGCC plant is less flexible compared to an ordinary combined cycle power plant. This is due to the inertia in connection with its process units mainly gasifier and ASU to generate and prepare the fuel at the conditions required by the GT. The operation flexibility of the IGCC plant is further affected when a CO_2 capture process, i.e. SEWGS process in this case, is introduced to the IGCC plant. To investigate the impacts of the SEWGS system on the operation flexibility of the IGCC plant, understanding of the dynamics of the SEWGS process and how fast it responds to load changes is required. It will provide an insight about the operability and load-following performance of the entire IGCC integrated with the SEWGS system at different part-load. In this section the results related to the dynamics of the SEWGS system as well as the performance of the GT fuel control strategy and operation flexibility of the IGCC integrated with the SEWGS at part-load operation are presented.

3.1. SEWGS dynamic characteristics

The detailed mathematical model which was developed previously is used to simulate the SEWGS system at different loads of the feed syngas [17, 18]. The CO_2 recovery and purity achieved from the simulation of the

SEWGS process at design condition are 95% and 99% respectively. To maintain the part-load performance of the SEWGS system in terms of the CO_2 recovery and purity same as the design condition, in addition to changing the load of the syngas, other parameters should also be varied. Key parameters influencing the performance of the SEWGS system are the cycle time, cycle configuration, number of the vessels, size of the vessels, rinse steam and purge steam consumption. In this work the number and size of the vessels as well as the cycle configuration are fixed when the load of the syngas is changed. On the other hand, amount of the purge and rinse steam as well as the cycle time are changed in a way to produce almost the same CO_2 purity and recovery rate as the design case. Simulation of the SEWGS system at different loads of the feed syngas is performed. Fig. 5 shows the load gradient of the SEWGS system achieved (seven data points). The best fit line to the data-sets is also drawn in Fig. 5 which has a slope of approximately 2.1 load%/min. This represents the load gradient (ramp rate) of the SEWGS system and indicates that the SEWGS process is very slow in responding to load changes compared to the GT. (load gradient of over 10%MW/min).

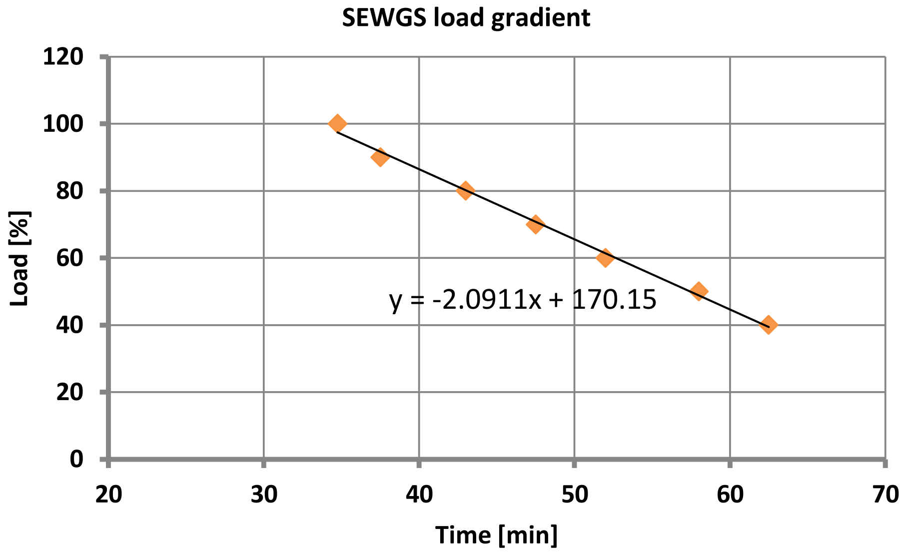

Fig. 5. Load gradient of the SEWGS system achieved from the different part-load simulations

3.2. GT fuel control system performance

The GT fuel mass flow rate is a function of the GT load. At any given load of operation, the control system adjusts the amount of the GT fuel mass flow rate according to its corresponding set-point value. Fig. 6 shows how the control system functions when two disturbances take place in the GT load in a stepwise manner. It is assumed that a 20% load reduction is given to the GT load, while the entire IGCC plant is operating at full-load. The GT then operates at 80% of its full-load for 400 seconds. Again, the load is increased back to the full-load level. Following the GT load changes, the fuel mass flow rate is controlled by the PI controller to approach its set-point value. As shown in Fig. 6 the designed control strategy performs properly and the fuel mass flow rate approaches its set-point after the transient response time is passed and the steady-state is reached. The flow rate fluctuations are reduced by the designed control strategy from ~±14% in the H_2-rich stream leaving the SEWGS system to ~±1-2%. Fig. 7 shows the impact of the anti-windup compensator included in the classical PI controller, as illustrated in Fig. 4, on improving the fuel mass flow rate behavior with respect to the transient response time. When a 20% reduction in the GT load occurs, the fuel mass flow rate is controlled in a way to approach its new set-point value when the new steady state is reached. However, it takes longer for the classic PI controller (without anti-windup) to reach the steady sate compared to the PI controller with anti-windup compensator. This shows how the anti-windup compensator improves the fuel mass flow rate behavior and reduces the transient state.

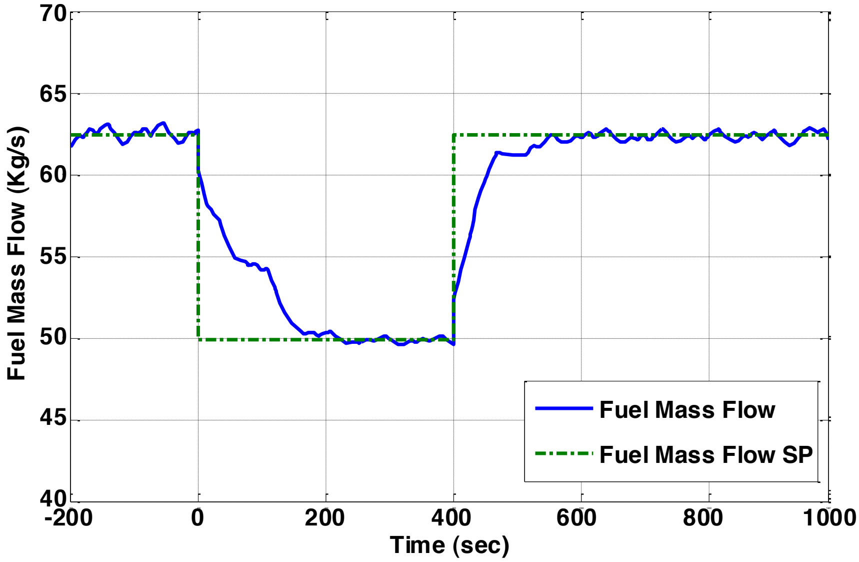

Fig. 6. GT fuel mass flow rate profile, 20% GT load reduction (stepwise) at time=0 seconds, 20% GT load increase (stepwise) at time=400 seconds

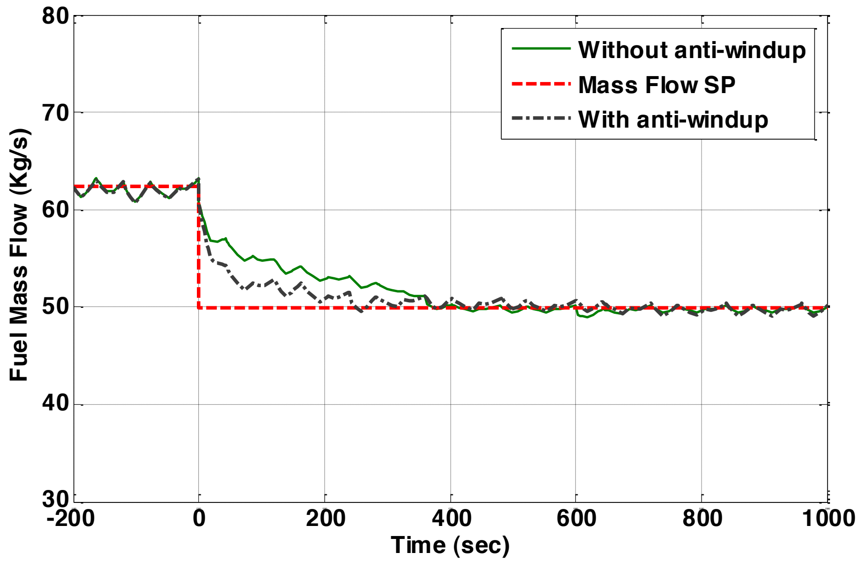

Fig. 7. Comparison of the GT fuel mass flow rate behaviour with and without anti-windup compensator, 20% GT load reduction (stepwise) at time=0 seconds

3.3. Load following capability of the SEWGS system at part-load operation

As mentioned in the previous section, a buffer tank is assumed after the SEWGS system to flatten out a portion of the fluctuations in the H_2-rich stream flow rate produced in the SEWGS system. The variation of the pressure in the buffer tank is important to ensure sufficient flow rate and pressure of the H_2-rich fuel to the GT during the operation. The pressure in the tank should fall within an acceptable range (between the pressure of the upstream SEWGS and downstream GT). Fig. 8 shows the buffer tank pressure variation when the 20% GT load reduction takes place.

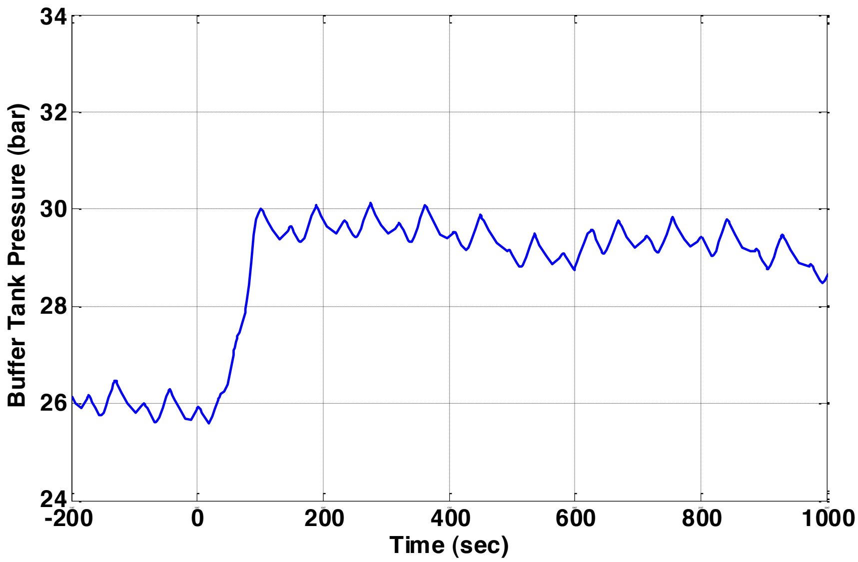

Fig. 8. Buffer tank pressure variation, 20% GT load reduction (stepwise) at time=0 seconds

As indicated in Fig. 8, the buffer tank pressure starts increasing once the 20% step reduction in the GT load is given. This is due to the imbalances occurring in the buffer tank inlet and outlet streams as a consequence of different response time of the process components to the load changes. The GT has a relatively fast dynamics. When the GT load is reduced, the fuel mass flow rate leaving the buffer tank is reduced correspondingly under the effect of the control system. On the other hand, it takes longer for the SEWGS system to respond to the GT load changes due to the slow dynamics. This will thus result in a pressure build-up in the tank, when the GT load is reduced. The tank pressure build-up continues until the transient response time is passed. Using the buffer tank improves the operation flexibility of the GT. As long as the acceptable pressure range in the buffer tank is met, the GT load can change without changing the load of the GT upstream process components. When the pressure in the buffer tank goes beyond the acceptable range, changing the load of the GT upstream process components is also required. In this case, load following capability of the process components which depends on their dynamic characteristics, is one of the main issues.

4. Conclusion

Part-load performance of an integrated gasification combined cycle (IGCC) power plant incorporating a sorption enhanced water gas shift (SEWGS) process for pre-combustion CO_2 capture is investigated. The SEWGS process with the multiple train arrangement operates in a cycle manner based on a pressure swing adsorption (PSA) process.

The H_2-rich stream which is the main product of the SEWGS is used as a gas turbine (GT) fuel. The periodic nature of the SEWGS process leads to the production of the H_2-rich stream with repeated fluctuations when the cyclic steady state is reached. To fulfill the requirements of the GT with respect to fuel pressure and heating value a control strategy including a buffer tank and a closed-loop PI controller is designed. A dynamic detailed mathematical model of the multi-train SEWGS process which was previously developed is used for simulation of the SEWGS process at different part-loads [17, 18]. Simulation results show the H_2-rich stream flow rate fluctuation is reduced from ~±14% to ~±1% under the effect of the designed control system. Also, when a disturbance in the GT load takes place, the fuel control system functions properly and provides the corresponding GT fuel flow rate and pressure after a new steady state is achieved. On the other hand, as a consequence of slow transient response of the SEWGS process to load changes (~2 load%/min as obtained from the part-load simulations), the mass balance of the buffer tank is also disturbed and pressure buildup in the tank is observed. However, addition of the buffer tank improves the operation flexibility of the GT as long as the buffer tank pressure variation is within a desired range. Different part-load operation strategies such as planned GT load changes can be considered to minimize the imbalances occurred in the system during the transient state of the IGCC plant and achieve a smooth operation of the IGCC integrated with the SEWGS process when the GT load is changed.

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